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GASBUGGY

POSTSHOT GEOLOGIC INVESTIGATIONS

**Lawrence
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Livermore

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PNE-G-11

NUCLEAR EXPLOSIONS—PEACEFUL
APPLICATIONS (TID-4500)

GASBUGGY
POSTSHOT GEOLOGIC
INVESTIGATIONS

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POSTSHOT GEOLOGIC INVESTIGATION—PROJECT GASBUGGY*

Abstract

In the Gasbuggy experiment on nuclear stimulation of natural gas flow, the nominal 26-kt nuclear explosive was detonated on December 10, 1967, at a depth of 4240 ft, in the Lewis shale some 40 ft below its contact with the Pictured Cliffs gas-bearing formation. Postshot exploration of the chimney and the surrounding fractured region consisted of geophysical, chemical, and radiochemical investigations in the redrilled explosive emplacement hole (GB-E) and in the redrilled preshot hole GB-2, which was offset about 300 ft from the emplacement hole. Gas production testing was also done to assess in a preliminary way the effects of nuclear stimulation. This report covers the investigations of chimney size and extent of fracturing.

The Gasbuggy explosion produced a rubble-filled chimney about 80 ft in radius and 333 ft high. The reentry hole penetrated only the upper portion of the chimney, which appears to consist of sagged and slumped rock strata, with a few rubble-filled voids. There is apparently no large void at the top of the chimney, as has been seen in other nuclear chimneys. It is thought that the horizontally bedded strata and the bulking characteristics of the rock with tensile failure are responsible for the lack of a void.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

The rock is fractured to some extent beyond the region of intense dynamic failure. This more distant fracturing takes place along pre-existing weaknesses such as bedding planes and, possibly, joints to at least 650 ft from the explosion, as evidenced by the offsets of drill hole casing in hole GB-2. Casing damage in the emplacement hole is observed at a depth of 3796 ft, or 444 ft above the explosion center. Brittle "Cliper" cables failed at the time of arrival of the shock wave to a distance of 500 ft from the explosion.

Caliper logs and borehole photography in postshot GB-2 (GB-2RS) show that the coal layers of the Fruitland formation are intensely fractured to at least 500 ft from the shot point. Density and caliper logs indicate significant porosity increases in the lower interval of the Pictured Cliffs formation in GB-2RS. This region of the reservoir evidently was intensely fractured to at least 375 ft from the shot. Similar evidence plus gas production data indicate that intense fracturing took place in the Lewis formation to at least 400 ft. The Lewis formation did not produce gas preshot.

The extent of intense dynamic fracturing is consistent with preshot estimates of 395 ft in the Pictured Cliffs formation and 490 ft in the Lewis formation. There appears to be a significant effect on the geometry of fracturing—beyond the range of intense dynamic failure—due to the bedded nature of the rock, the pre-existing weaknesses such as jointing, and, especially, the low density coals.

The definition of changed effective permeability and its effect on the gas production is not as well documented as desired, but the deformational effects of the experiment, in light of the limited data, are at least as encouraging to nuclear stimulation as the preshot expectations.

Introduction

The Project Gasbuggy nuclear explosive of nominally 26-kt yield was detonated on December 10, 1967, at 12:30 Mountain Standard Time at a depth of 4240 ft below the ground surface, about 55 miles east of the city of Farmington, New Mexico. The location of the explosion was 1770 ft from the west line and 1218 ft from the south line of Section 36, Township 29 North, Range 4 West, in Rio Arriba County, New Mexico, corresponding to geodetic coordinates of latitude $36^{\circ} 40' 40''$ North, longitude $107^{\circ} 12' 30''$ West, at an elevation of 2964 ft above mean sea level. The detonation occurred in the Lewis shale formation of the San Juan Basin, about 40 ft below the Lewis shale contact with the gas-bearing Pictured Cliffs sandstone. Indications are that the explosive performed satisfactorily.

The purpose of the Gasbuggy experiment was to determine to what extent a low-permeability natural gas formation can be stimulated by an underground nuclear detonation and to identify the detonation-associated effects which cause the stimulation. Specifically, the experiment was designed to achieve these objectives:

1. To measure the changes in the deliverability and ultimate recovery of the gas, and insofar as possible to identify the changes responsible.
2. To measure any radioactivity of the gas, to study the thermodynamics and chemical reactions of the mixture of gaseous fission products and methane, and to evaluate any necessary control measures.
3. To measure and to evaluate the generation and propagation of seismic energy within the San Juan Basin as part of a continuing study of ground motion and its effect on structures.

The preshot program and the preparation for the shot-time measurements were described in the Preshot Summary Report.¹

Early postshot data was reported in the Gasbuggy Preliminary Postshot Summary Report.² Details of the drilling and testing operations have been reported by Cutler and Kendrick,³ and reservoir evaluation by Ward and Lemon.⁴ A status report by Smith and Momyer⁵ discusses the results of chemical and radiochemical investigations as they relate to quality of the postshot gas.

This report summarizes the results of postshot exploration with emphasis on the rock deformation that resulted from the explosion.

Summary of the Geologic Setting

The stratigraphic panel in Fig. 1 illustrates the major rock units affected by the Gasbuggy explosion.

The uppermost Ojo Alamo formation is a fine- to coarse-grained sandstone. It is the closest source of mobile water to the explosion (approximately 600 ft above the explosion center). This aquifer has a permeability of approximately 1 md (millidarcy). Preshot analyses indicated that if the chimney or fractures from it intercepted this aquifer, water could migrate into the chimney, but that the flow rate under worst conditions could be handled by pumping.

Separating the Ojo Alamo formation from the gas-bearing Pictured Cliffs formation are the interbedded shales, siltstones, and coals of the Kirtland-Fruitland formations. The arbitrary division at approximately 3800 ft depth is the uppermost coal lens.

The basal coal member is about 35 ft thick. Because of the compressibility of the low-density coal, this rock was expected to absorb much of the energy

GEOLOGIC SECTION

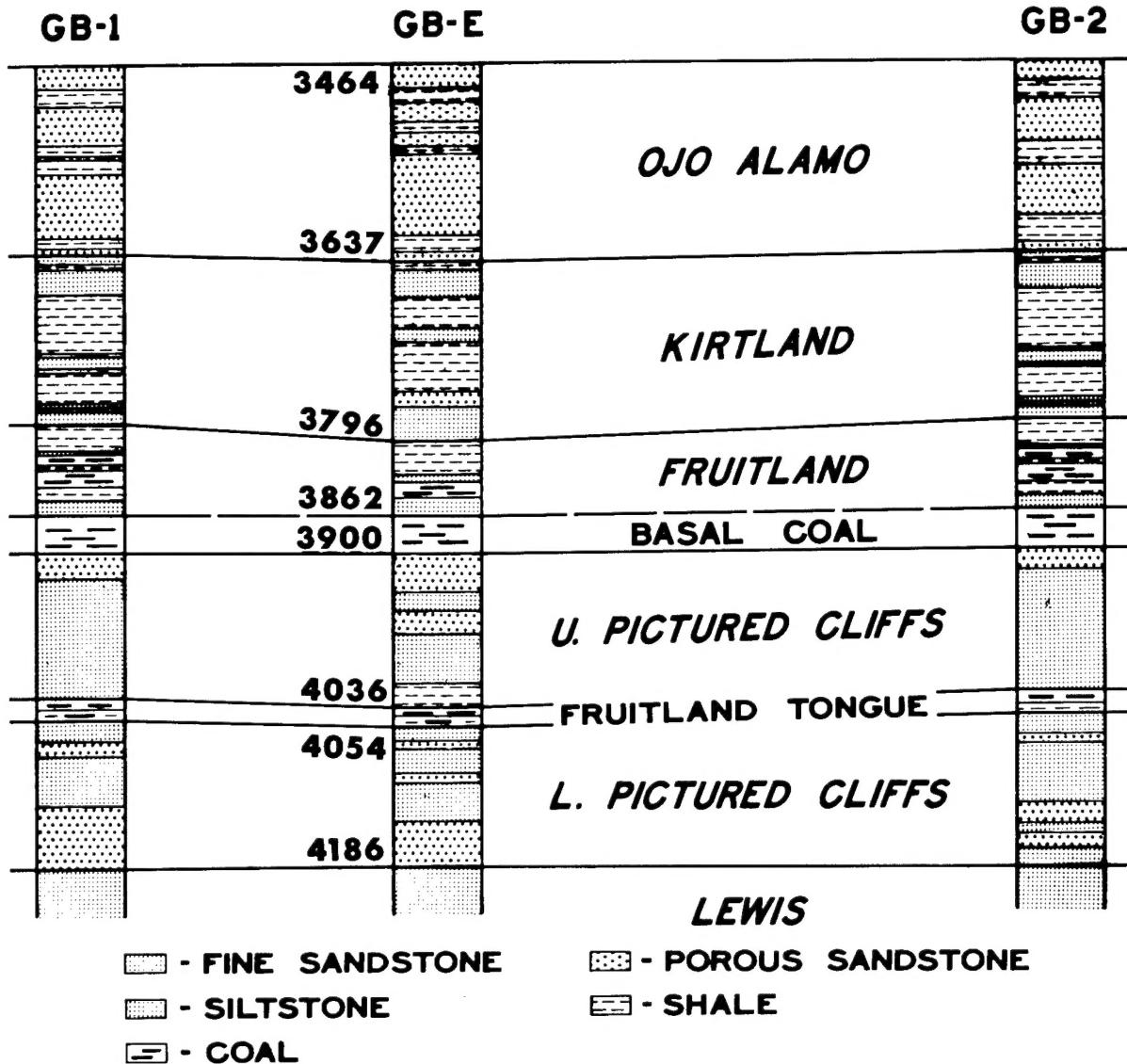


Fig. 1. Geologic section at Gasbuggy site.

of the stress wave generated by the explosion. Significant new fracturing was not expected to occur in the shale above the basal coal. Fracturing in this sense refers to intense dynamic failure of the matrix strength of the rock, and not failure along such weaknesses in the rock as joints, bedding planes, etc. Prediction of intense dynamic rock failure is based on the strength properties of core samples. It is very difficult to predict failure along rock weaknesses.

With the assumption that the basal coal would remain competent in tension, the height of the chimney was expected to terminate at the top of the Pictured Cliffs formation.⁶ Assuming that the lower Fruitland had numerous pre-existing weaknesses that would fail in tension, the chimney height was expected to be at the top of the Fruitland section,⁷ at approximately 3800 ft depth. It was recognized in addition that the actual chimney height is also dependent upon the bulking characteristics of the failed rock fragments.

The Pictured Cliffs section is predominantly massive, fine-grained sandstone containing thin interbedded shale beds and lenses. The more porous sections, containing the bulk of the gas reserves, are shown stippled in the figure. The upper and lower Pictured Cliffs units are divided by a tongue of interbedded shale, siltstone, and coal of the Fruitland formation.

Gas production in the Pictured Cliffs formation at the Gasbuggy site is characterized by gas flow primarily along natural joints, fractures, and bedding planes. The gas flow in the rock matrix is of lesser importance to production rates because of the low in situ permeability. The permeability of dry, unconfined core samples is about 0.16 md. Pressure buildup data indicates an in situ permeability of approximately 0.01 and 0.02 md, assuming a producing interval 150 ft thick. Limited testing of undried core samples under confining pressures equal to the hydrostatic head and overburden pressures indicate possible in situ permeabilities on the order of 0.001 md.

The upper 100 feet of the Lewis shale is predominantly an interbedded sequence of shale and siltstone. The included water and carbonate minerals play an important part in determining the rock-vapor working gas generated by the explosion and also in determining the disposition of certain radioactive species, as discussed by Smith and Momoyer.⁵ The water content is about 4%, and the carbonate minerals are about 9% by weight of the rock.

Exploration

Figure 2 is a plan view of the pre- and post-shot hole locations, showing the surface locations of the holes and their locations in the vicinity of the shot point elevation. Care was taken in locating these holes to avoid possible major

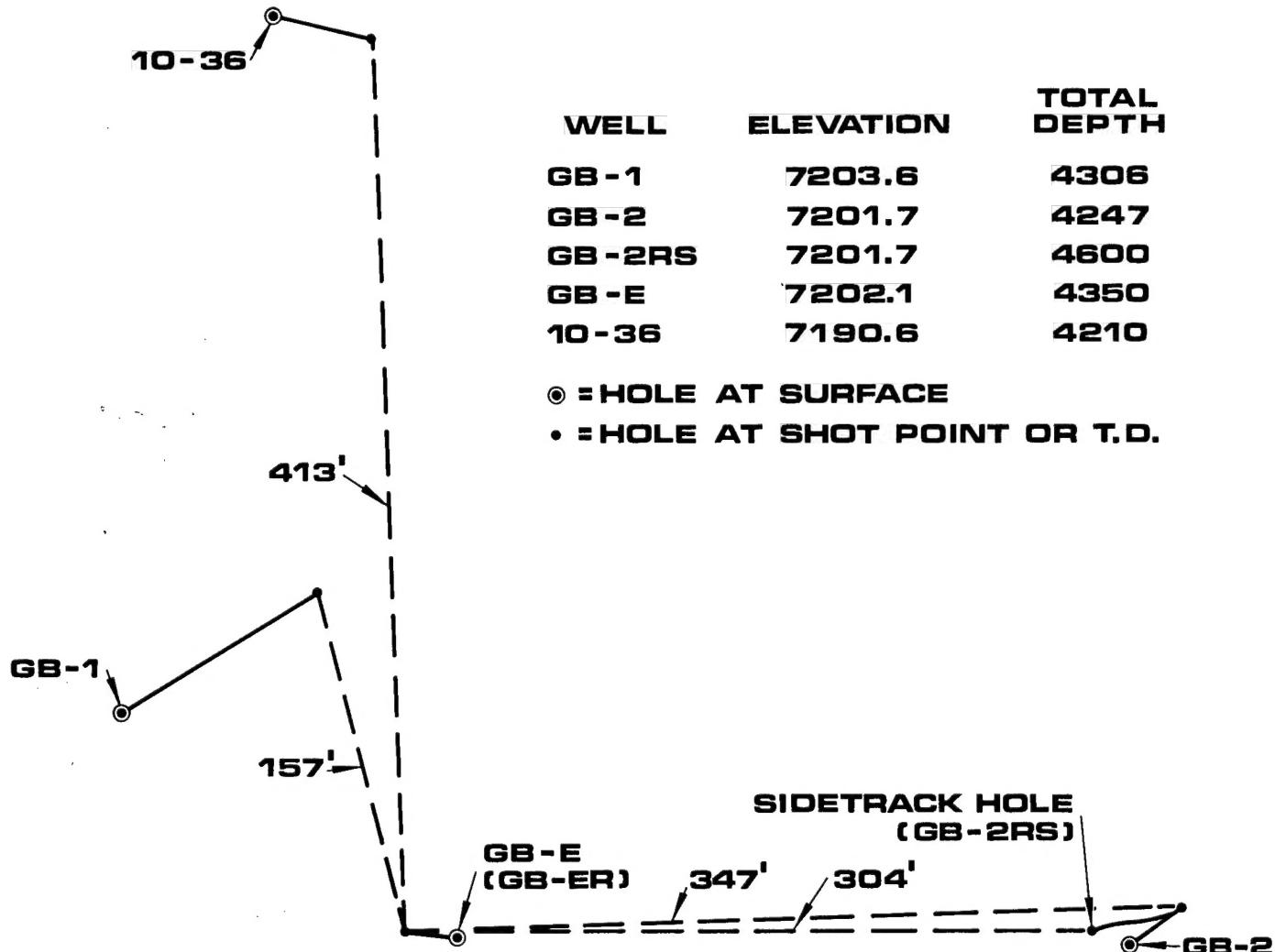


Fig. 2. Plan view of tops and bottoms of holes at Gasbuggy site.

structural lineaments that might have yielded abnormally high gas production if intersected by fracturing from the explosion.

Hole 10-36 was completed in 1956 as a producing gas well. GB-1 and -2 were drilled preshot as part of the site definition; GB-1 contained dynamic effects instrumentation at the time of the explosion. GB-E was the emplacement hole for the nuclear explosive.

Hole GB-ER was the postshot reentry of the emplacement hole, made by drilling out the grout inside the 7-in. casing on which the explosive was emplaced. The hole was drilled to 3916 ft, where offset casing prevented further progress. A series of geophysical logs and production tests were made in this hole.

Hole GB-2R was the postshot reentry of preshot hole GB-2. Reentry was made to a depth of 3812 ft, where offset casing was encountered. A sidetrack hole, GB-2RS, was drilled from 2690 to 4600 ft. A new suite of logs was run to compare with the preshot logs run in GB-2.

Postshot Environment

Figure 3 is a schematic cross section of the postshot Gasbuggy environment, as it is presently interpreted. The preshot holes are dashed, those drilled postshot are solid. Figures 4-6 illustrate the data on which this picture is based.

GB-ER encountered several casing breaks and two voids above the chimney top at 3916 ft. There was no large void at the top of the chimney and this region is interpreted as consisting of broken and sagged beds of rock. The chimney radius is drawn at 80 ft, the preshot prediction which is borne out by production data.⁴

Fracturing in the sense of movement along pre-existing rock weaknesses extends at least as far as the upper boundary shown. The intermediate region

of fracturing indicates more intense failure of the rock, with breakage of the matrix or cementing material. The coal is failed so that it caves when unloaded.

Both reentry holes were plagued with water leaks. It is certainly possible that this leakage is confined to failed or permeable cement. On the other hand, the indicated extent of fracturing along bedding planes suggests the real possibility of vertical fracturing into the Ojo Alamo along pre-existing joints.

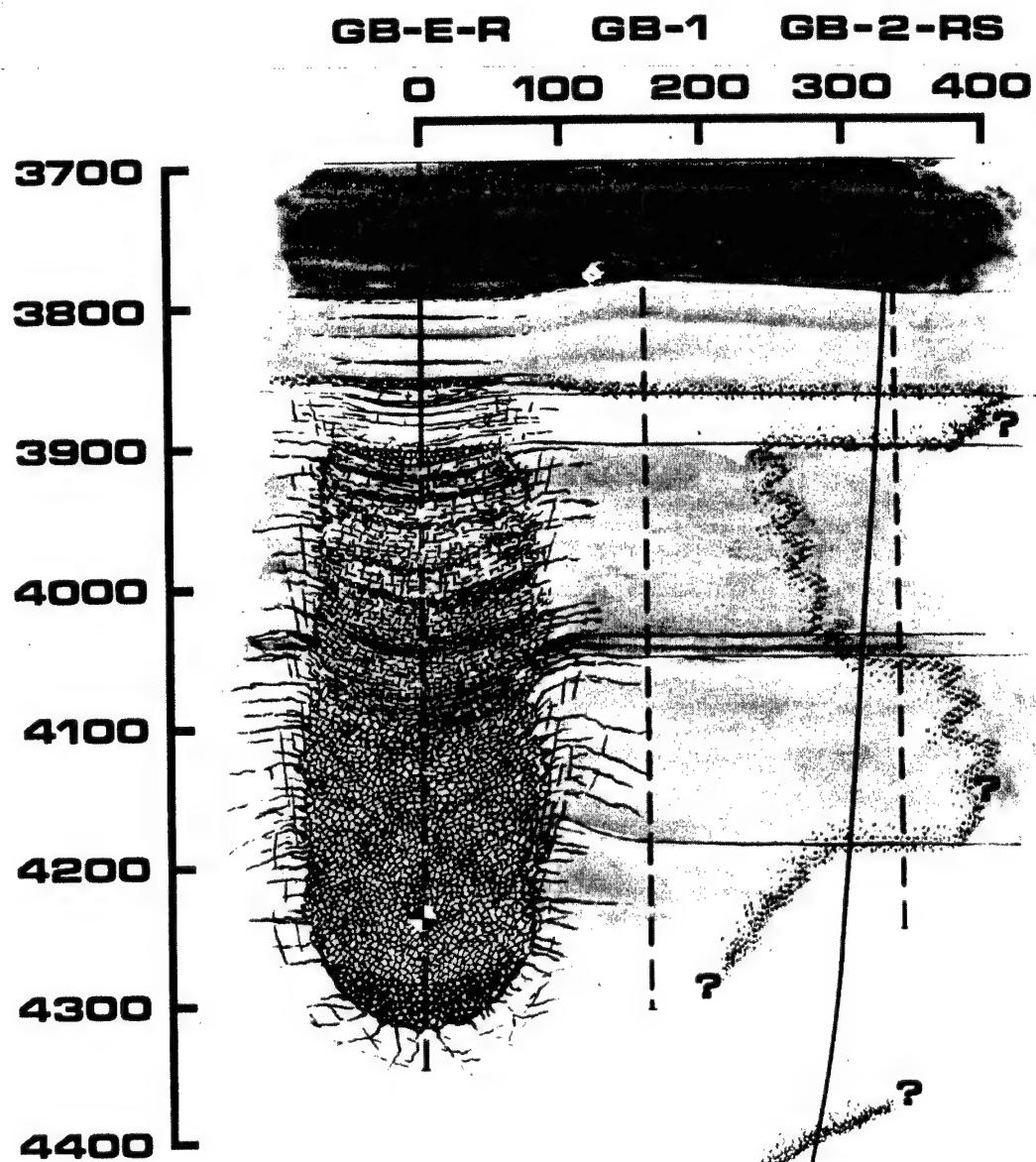


Fig. 3. Vertical cross section through Gasbuggy chimney and surrounding area, as determined from postshot explorations.

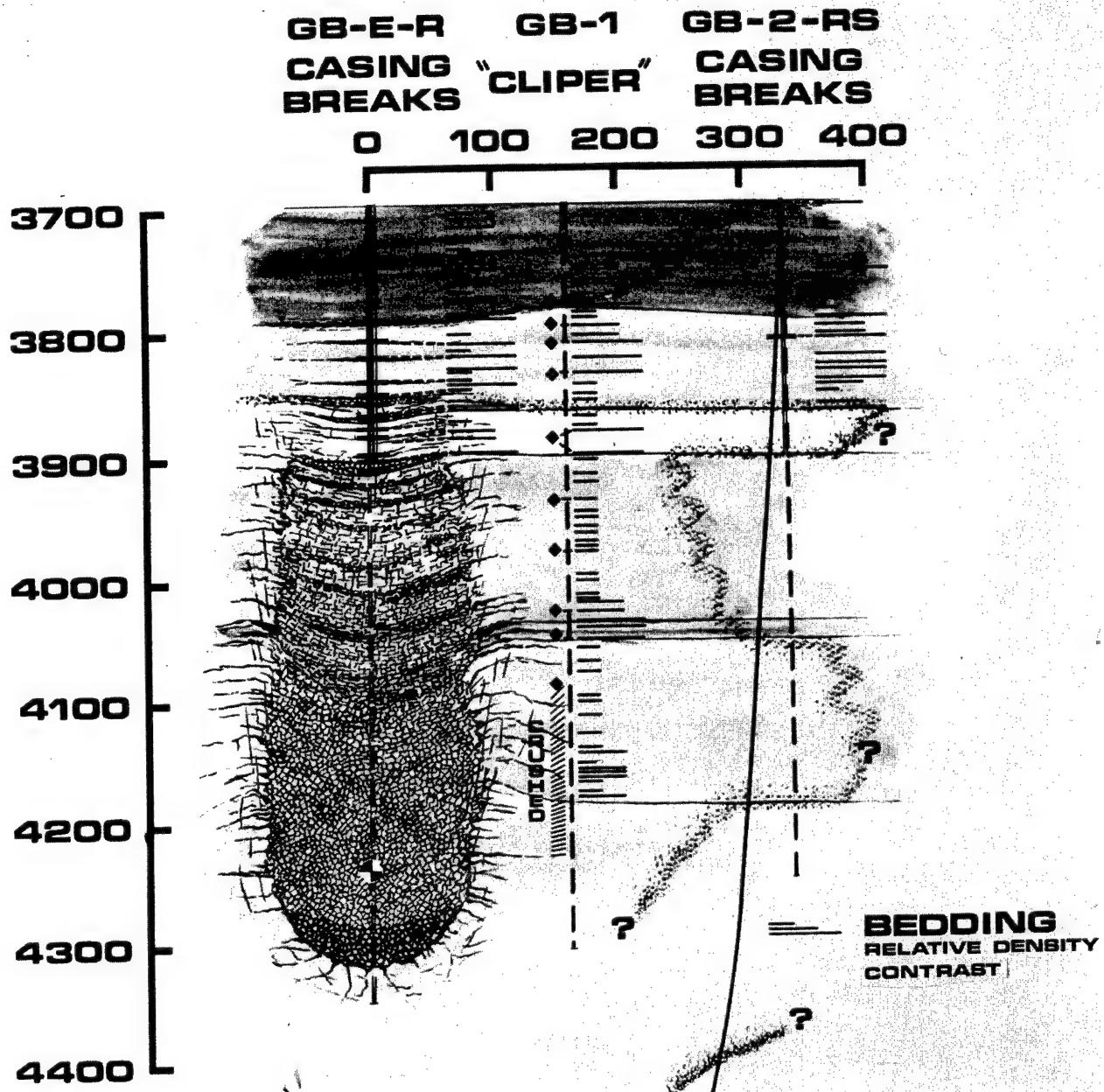


Fig. 4. Data from "Cliper" cables and casing breaks superimposed on cross section through Gasbuggy chimney.

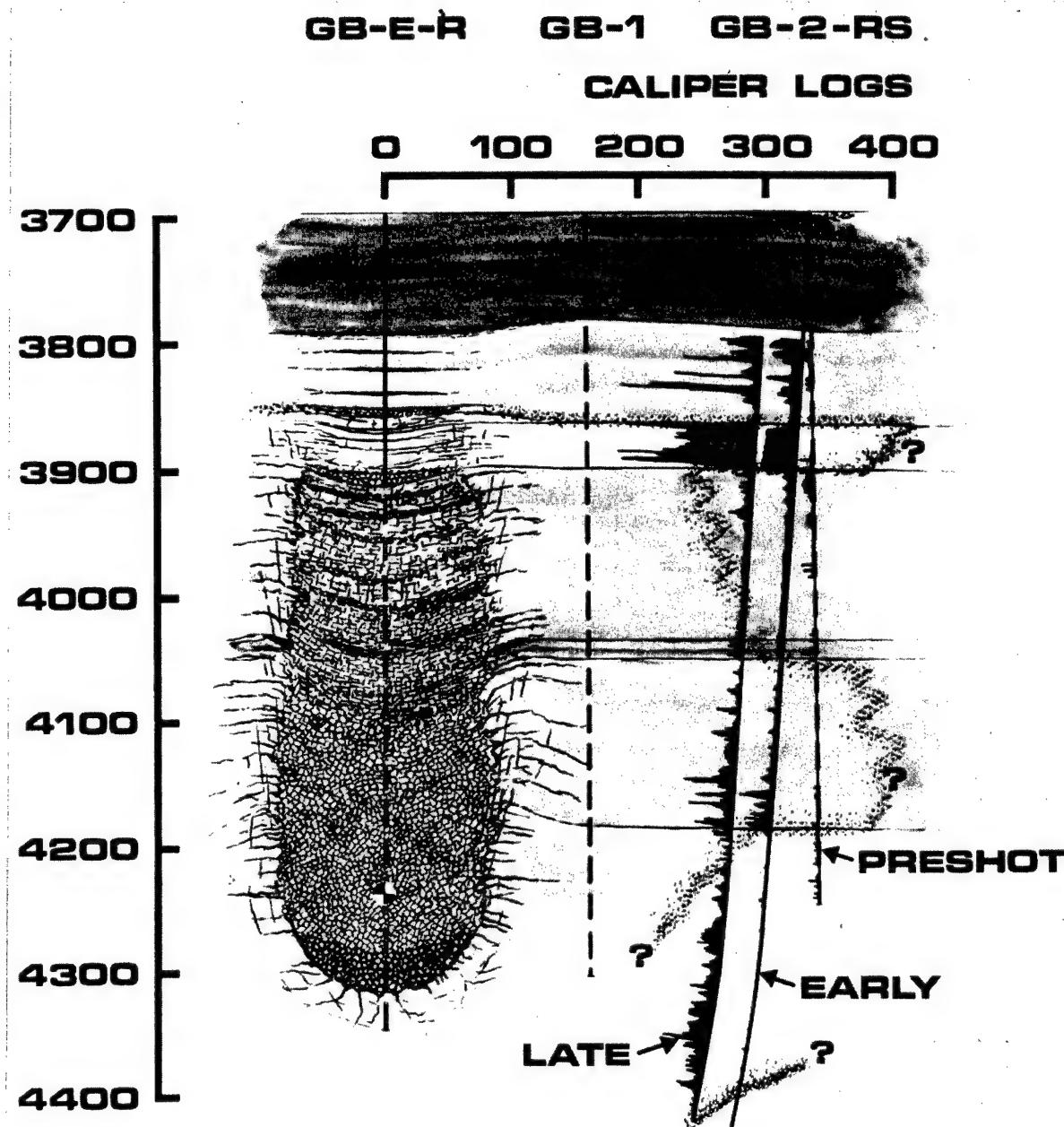


Fig. 5. Comparison of pre- and post-shot caliper logs, superimposed on cross section through Gasbuggy chimney.

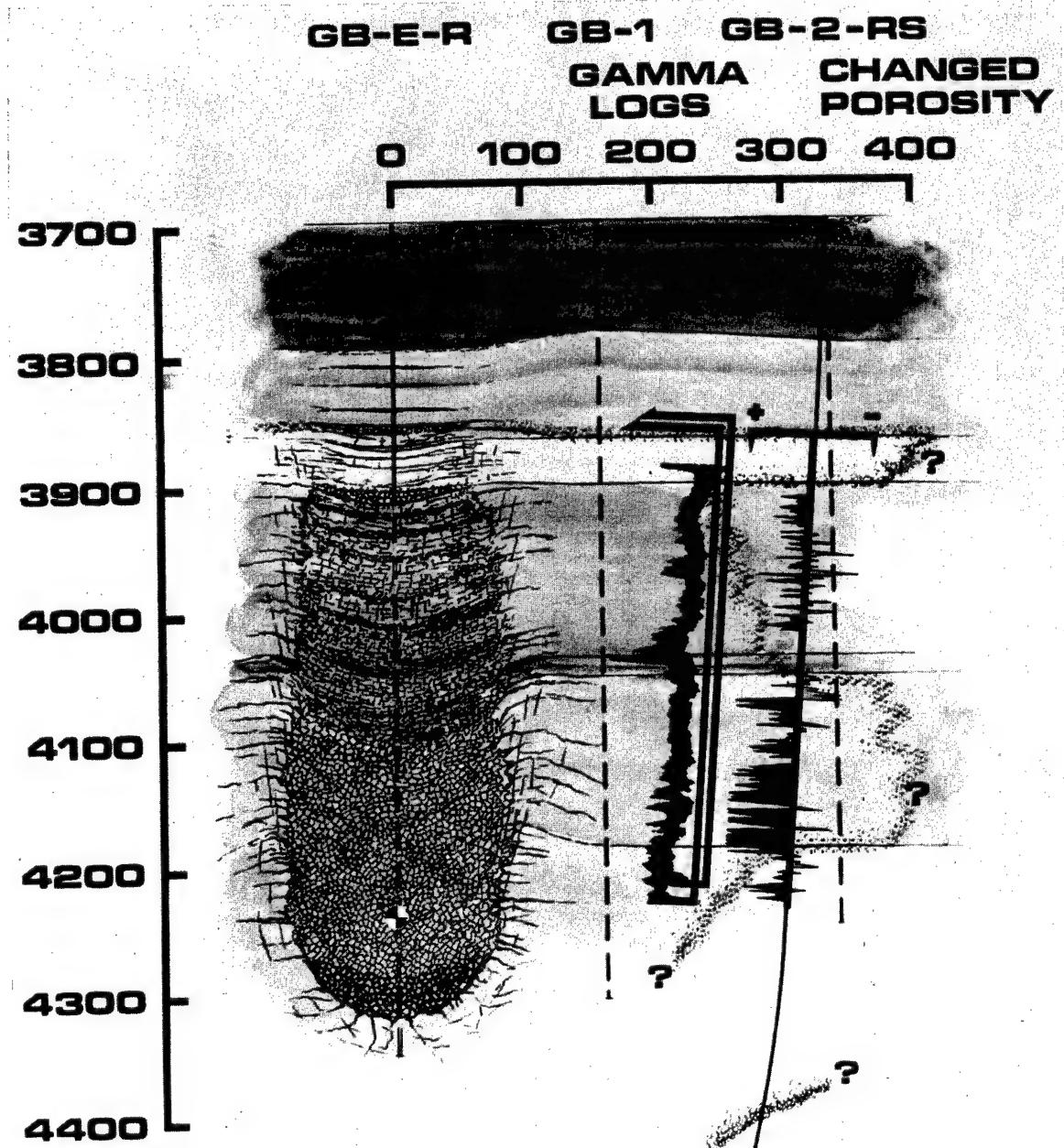


Fig. 6. Changes in porosity and comparison of pre- and post-shot gamma logs, superimposed on cross section through Gasbuggy chimney.

Figure 4 shows the distribution of casing and cable breaks correlated with the preshot bedding in the rock. "Cliper" cables in hole GB-1 monitored the progress of the strong close-in shock. These brittle cables with a ceramic dielectric utilize a reflected high-frequency electrical pulse to continuously measure the electrical length of the cable. As the cable is crushed by the advancing shock, the indicated length decreases accordingly. Thus, the depth and time of cable breaks are determined. The data shows continuous crushing of the cable at a time coincident with the arrival of the shock wave. Above the crushed region, there are discrete breaks also developing at the time of arrival of shock.

The bedding planes are chosen at the contacts of the interbedded rocks of significantly different densities. The major bedding planes are where the density contrast of the adjacent rocks is the greatest. There is an apparent close correlation between both the casing and "Cliper" breaks with these bedding plane weaknesses. It can be presumed that weaknesses associated with jointing would respond similarly. (It should be noted that there are two concentric casings in GB-E, and a single smaller casing in GB-2.)

The pre- and post-shot caliper logs shown in Fig. 5 give a gross indication of the failed condition of the rock encountered in GB-2RS. For these logs, the horizontal scale is greatly exaggerated. Note that the basal coal of the Fruitland was competent preshot and caving postshot. The early postshot log, run 10 hours after drilling stopped, indicated caving conditions in the lower Pictured Cliffs unit. The late log was run 35 hours after the hole was completed. Small amounts of water started seeping into the hole during the drilling of the sidetrack hole GB-2RS. This probably accelerated the caving of the rock, since the clay minerals are reactive with water. This later log shows pronounced caving of the Lewis to a depth of 4400 ft, and less caving to the total depth of 4600 ft. This is suggestive

of shot-induced fracturing which would allow greater penetration of water into the shale, which in turn accelerates caving.

Cherry et al.⁶ predicted that compressive brittle failure would extend laterally in the Pictured Cliffs formation 395 ft. A similar calculation by Larson⁸ indicates failure in the Lewis shale to 490 ft. Figures 5-7 indicate consistency with those predictions. In Fig. 5 it is indicated that the lower Pictured Cliffs unit is more intensely failed than the upper unit, and possibly this hole is located near the limits of intense dynamic failure of the sandstone.

The relative changed porosity of the Pictured Cliffs formation (Fig. 6) shows a pattern similar to the caliper log—the lower unit has increased porosity significantly more than the upper unit. The pre- and post-shot gamma-ray logs indicate that the general rock character is the same in holes GB-2 and GB-2RS. That is, there are no pronounced lateral facies changes. The plot of changed porosity was constructed from the calculated porosity of the pre- and post-shot "sidewall-compensated density logs." Errors in this technique introduced porosity exaggerations, so the absolute values are accordingly somewhat in doubt, but the relative changes are considered valid. If one assumes no compaction of rock at this distance, the decreased porosity shown on the right gives an indication of the statistical uncertainty of this approach.

One sidewall sample in the basal Pictured Cliffs and five in the upper Lewis shale were recovered in spite of adverse sampling conditions. Examination by Borg⁹ indicates that the quartz grains are not significantly fractured and that the rock failure at this distance is primarily in the cementing matrix.

Figure 7 illustrates the effects of the explosion on the gas production characteristics in hole GB-2RS. On the left are the pre- and post-shot natural gauge data. This illustrates more general gas entry postshot than preshot. The total production appears to be significantly greater postshot than preshot,

**NATURAL
GAUGE**

(MCF/D)

**TEMP-
ERATURE**

(F. DEGREES)

**PACKER -
FLOWMETER**

GB-2 RS

% OF

TOTAL FLOW

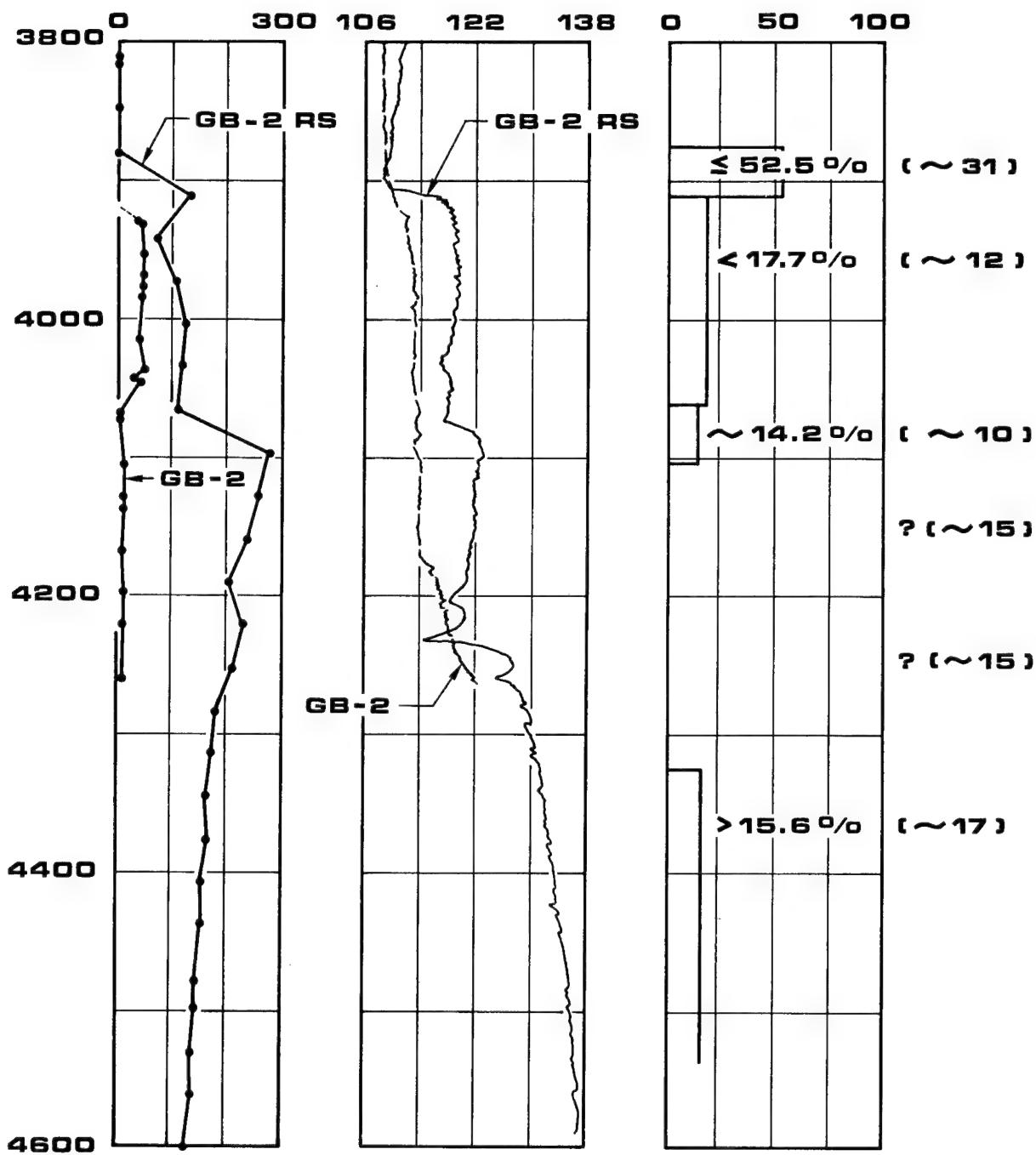


Fig. 7. Comparison of pre- and post-shot gas production data in drill holes GB-2 and GB-2RS.

but a quantitative increase is not possible to determine because the holes had different drilling and casing programs. The flowing temperature logs give more specific detail of the gas entry locations. Major entries occur just below the basal Fruitland coal and below the Fruitland tongue. Significant entries now exist in the upper Lewis, which was relatively barren preshot. There are entries in the Lewis to the total depth of 4600 ft, indicating increased permeability to that depth. Comparison of gas chromatographic data between the input drilling gas and the return gas indicate that natural gas was flowing into the hole from the surrounding rock all the way to the bottom.

A specially designed packer-flowmeter was used to define the gas entry distribution in a more quantitative fashion. The bad hole conditions of caving and water leakage resulted in few packer seats and caused jamming of the spinner elements so that the data acquired is less definitive than desired. Figure 7 shows the data and its quantitative limitations. Of special significance is that greater than 15.6% of the total gas from the hole comes from below 4325 ft. The estimated gas entry distribution at the extreme right of the figure is an attempt to use the natural gauge and flowing temperature data to fill in the gap in the packer-flowmeter data.

The production data in this hole should be considered minimal because there is thought to be a high probability of skin damage. As the hole was being drilled, there was believed to be a slight water leak entering the hole at a depth of approximately 3812 ft. Also, the drilling gas consisted of about 8% propane and butane fractions. Continued water entry and caving of the hole prevented continued use of this hole for gas production testing. Only enough gas was produced to allow migration of a small amount of radioactive gas from the chimney to this hole. The indicated temperature increase postshot, shown

in Fig. 7, would suggest communication with the hotter chimney region, as would the observed increase in the CO₂ content of the gas after limited flow.

Conclusions

Returning to Fig. 3, it is apparent that the rock is fractured at least 650 to 700 ft from the explosion along pre-existing weaknesses in the rock. The indicated more general breakage of the Pictured Cliffs and Lewis shale is consistent with preshot predictions, as is the chimney height. Accurate quantitative determinations of change in permeability and gas production as a function of degree of fracturing are not possible at this time. There appears to be a significant effect on the geometry of fracturing due to the bedding of the rock and especially the low density coals. The general rock deformation results of the experiment, in the light of the limited data, are at least as encouraging to nuclear stimulation as preshot predictions had indicated.

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TECHNICAL AND SAFETY PROGRAM REPORTS
PROJECT GASBUGGY

A. TECHNICAL REPORTS - (already issued)

<u>Authoring Organization</u>	<u>Report No.</u>	<u>Report Title</u>
EPNG/AEC/USBM/LRL	PNE-1000	Project Gasbuggy (Feas. Study Rpt.)
LRL	PNE-1001	Pre-Shot Summary
LRL	PNE-1003	Preliminary Post-Shot Summary
EPNG	PNE-G-9	Drilling & Testing Operations
LRL	PNE-G-10	Gas Quality Investiga- tion Program Status Rpt.
LRL	PNE-G-11	Post-Shot Geologic Investigation
USBM/EPNG	PNE-G-13	Status of Reservoir Evaluation

B. TECHNICAL REPORTS - (to be prepared)

SL	PNE-1002	Free-Field & Surface Ground Motions
LRL	--	Prediction & Results of Dynamic Effects
LRL	--	Analysis & Interpretation of Gaseous Radioactivities
LRL	--	The Gasbuggy Seismic Source
LRL	--	Response of the Navajo and El Vado Dams
EPNG/USBM/LRL	--	Reservoir Geology
EPNG/USBM	--	Post-Shot Flow Tests
EPNG/USBM	--	Reservoir Analysis

C. SAFETY REPORTS - (already issued)

NV PNE-G-12 Operational Safety Aspects

D. SAFETY REPORTS - (to be prepared)

EIC	PNE-1006	On-Site Radiological Safety
USPHS	PNE-1007	Off-Site Radiological Surveillance
ESSA/ARFRO	PNE-1008	Weather and Radiation Predictions
II	PNE-1009	Ground Water Safety Evaluation
ERC	PNE-1010	Analysis of Ground Motion & Containment
USBM (BuMines)	PNE-1011	Mine & Well Safety
JAB	PNE-1012	Structural Response
USGS	PNE-1013	Geology & Hydrology
USC&GS	PNE-1014	Seismic Measurements

E. ABBREVIATIONS OF ORGANIZATIONS

EIC	Eberline Instruments Corp., Santa Fe, N.M.
EPNG	El Paso Natural Gas Co., El Paso, Texas
ERC	Environmental Research Corp., Alexandria, Va.
ESSA/ARFRO	Environmental Science Services Administration/ Air Resources Field Research Office, Las Vegas, Nev.
II	Isotopes, Inc., Palo Alto, California
JAB	John A. Blume & Associates, San Francisco, Calif.
LRL	Lawrence Radiation Laboratory, Livermore, Calif.
NV	USAEC Nevada Operations Office, Las Vegas, Nevada
SL	Sandia Laboratory, Albuquerque, N.M.
USAEC	U. S. Atomic Energy Commission
USBM	Bureau of Mines, U. S. Department of the Interior
USC&GS	U. S. Coast & Geodetic Survey, Las Vegas, Nev.
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